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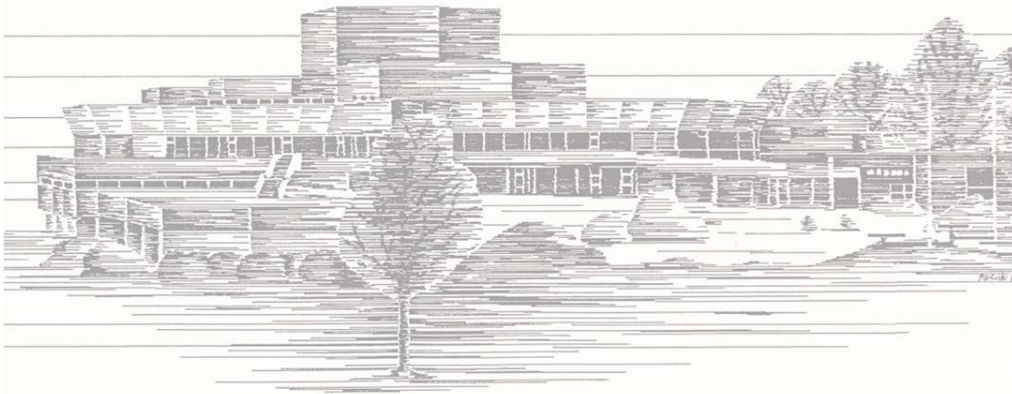
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# Intermittently Fed Anaerobic Digestion: Requirement and Process Control

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## Abstract

The electricity network is undergoing a change due to reducing costs for renewable energy sources. Subsidy programs for renewable energy sources are changing and the funding available is being reduced. This will have an impact on anaerobic digestion which in some cases may struggle financially. Overfeeding is one of the most common mechanisms of inhibition in the process, and by shifting to intermittent feeding for on-demand production, this change will provide more information about the digestion process and could be used to detect the beginning of inhibition due to overfeeding. This paper discusses the shift towards intermittent production and how this change can be used to monitor the anaerobic digestion process.

## 1. Introduction

Climate change is an ongoing concern for the world, as the combustion of fossil fuels is causing long term change to the environment [1]. Consequently, there has been an increasing shift towards the use of renewable energy sources [2]. Solar and wind power have seen particular increases, where for example in many countries there are subsidies for electricity generation from renewable energy sources. These subsidy programs have helped growth of the market, and enabled lower prices for new installations due to the cost decreasing as the market has increased in size.

One of the draw backs of increasing the amount of energy from solar and wind power, is that both of these power sources are dependent upon the weather. Solar power will only work during the day time, and during cloudy periods the output will be significantly reduced. Similarly for wind power, the output will vary with the wind which can change significantly over a short period of time. As a larger proportion of energy is created by weather dependant renewable sources, this puts the electrical grid under greater stress. The electricity supplied to the grid must match the demand very closely, otherwise the power provided will no longer meet the specifications, and can result in damage or power cuts to connected equipment [3]. For the traditional electricity networks, balancing is typically performed by varying the output power from gas turbines, with some further assistance provided by pumped storage. However, the amount of energy stored at a pumped storage

facility is relatively small compared to the demands of the electricity network, and gas turbines are still using a fossil fuel. A coal power plant, in addition to using fossil fuels, will take much longer to adjust the production rates, and so cannot quickly change from a low power output to a high power output, as would be necessary to meet the demand as a result of the wind dropping.

Anaerobic digestion is a source of renewable energy that operates by putting organic waste in to a tank and allowing microbes to break down the organic material. One of the outputs from this process is biogas, which contains a significant amount of energy and can be burnt in a CHP (Combined Heat & Power) unit for creating both electricity and heat. The use of anaerobic digestion is of further interest, because unlike solar and wind power sources, it is not dependent upon the weather. A typical anaerobic digestion plant will have the ability to store gas for a short time, and furthermore, biogas production can be controlled by varying the feeding amounts and times. This allows the system to be used as a renewable energy source, over which the plant operator has control over the time at which biogas is produced.

A CHP unit running on biogas could be operated in a similar way as the gas turbines used at the time of writing. This would allow anaerobic digestion to provide a renewable energy source that is capable of contributing to the balancing of the energy grid. Furthermore, generally the weather can be predicted with a high degree of accuracy over a short time, and electricity consumption trends are largely predictable using historical data. It would be possible in the future that a biogas plant operator can anticipate an increase of demand a day in advance for example, and feed the biogas plant an increased amount of biomass before the electrical demand increases. This will produce additional biogas as it is required, and will allow the plant operator to generate more electricity and support other renewable energy sources.

Such a mode of operation is in contrast to the current operating methodology of biogas plants, which is to run the CHP at the maximum power possible for as much time as possible. That is as a result caused by two boundary conditions, firstly the subsidies provided from the government to the plant operators, and secondly as a result of the agreements that are contracted between biogas plant operators and the electricity companies that are buying the electricity. At the time of writing, in Germany the subsidy program for the production of electricity from biogas has been significantly limited [4] with a cap on the total installed production that will be awarded subsidies, meaning that in the future as the existing agreements expire, it may no longer be financially viable to run a biogas plant for the electricity cost alone. The electricity price is generally higher when it is required for balancing the grid, and so by selling electricity when the price is higher, it may be possible for biogas plants to still operate at a profit, when compared to operating continuously and selling the electricity for the lower "base load" price [5].

There is a further complication with the operation of a biogas plant: overfeeding the plant can be extremely expensive. As the anaerobic digestion process features many groups of microbes, what can happen at high feeding rates is that one group of microbes will work

faster, but another group will not be able to keep up. This can result in the first group of microbes poisoning the digester, which ends up in a cycle whereby the anaerobic digester is no longer able to operate. When this happens, the entire digester must be emptied, the contents must be disposed of, and the fermentation process must be started again from the beginning. This process involves a lot of time and cost, and it can take up to 3 months until the anaerobic digester is running at the same level as before the failure. This results in an understandable high level of caution from the plant operators concerning modifications in the operation process. Clearly it is better to run a biogas plant slightly below its optimum level, rather than risking a huge cost and reduction of income for 3 months.

Anaerobic digesters traditionally do not have a large number of instruments to monitor the process. One study performed a survey of over 400 plants and found that the process is mostly analysed using laboratory methods, and that on-line measurements are lacking [6]. Laboratory analysis requires time and a skilled operator, and also requires sample preparation, and so can require several hours or even longer until results are available. When trying to closely monitor and control a biogas plant, this lack of real time information about the performance of the plant is a problem, as it is a further reason that the biogas plant would be operated conservatively. For example in the scenario where inhibition starts to occur, with an online monitor this could be detected in a matter of minutes and compensated for, however for a system where the only testing performed is a laboratory analysis of a sample once a week, then the process may have become inhibited before the sample has even been analysed. Thus by improving the state of instrumentation and monitoring of the biogas plant, the safety margin can be reduced and the output of the biogas plant can be increased. Clearly this can increase the amount of income from exporting electricity from using the same equipment, and so better availability of affordable online sensors would enable more efficient operation of biogas plants.

## **2. The goals of anaerobic digestion**

There are two operating scenarios that describe the majority of anaerobic digesters in operation. The first scenario is that where the primary goal is the handling of waste, such as waste water treatment whereby the waste water must be purified and organic matter in the stream must be reduced. For water with a sufficiently high concentration of organic matter, anaerobic digestion is used and methane is a by-product, which is profitable for the digester operator to capture and burn in a CHP allowing the use or sale of electricity and generation of an extra income stream. There is a similar situation for disposal of municipal food waste and garden waste, where the waste must be disposed of properly as without proper disposal the food waste formerly has been sent to a landfill site where it would slowly be degraded over a longer time scale, and the methane released would contribute to the greenhouse gas effect. Today organic waste often is incinerated, a process of low or zero energetic output caused by the high degree of moisture of the waste.

By processing the food waste at centralised anaerobic digesters, the released methane can be captured and utilised. By a well-planned handling process, extra income can be generated by capturing the released methane and using it for electricity production. There may still be advantages in these scenarios to optimisation, for example if the incoming waste is higher than the loading rate then the extra waste is likely to be incinerated, incurring additional costs.

The second scenario is that of an anaerobic digester which is operated primarily for the generation of financial profits and is not concerned with the handling of organic waste. These digesters represent the majority of the anaerobic digesters that are present in Germany as of 2017. In these cases, crops are grown specifically to feed anaerobic digesters, and an increase in loading capacity will give an increase in the power generation and thus increase in income. This is of importance as subsidies are being reduced and a more flexible operation is necessary today. Improvements in operation can ensure that such systems maintain profitability and can help to contribute to a renewable energy grid.

### **3. Electricity production from anaerobic digestion**

In Germany, in 2015 there were 10551 operating biogas plants that were identified [7]. In 2015, the reported total installed electrical power was 4379MWe [7]. As of 2011, in Germany between 90 and 95% of biogas plants were operating on a mixture of manure and crops [8], which makes them the vast majority of AD plants in Germany and also means that this large amount of plants will be faced with financial challenges once the subsidies are cut.

By comparison, in the United Kingdom, as of March 2017, there are 747MWe of operational landfill gas plants, and 38MWe of operational sewage sludge digestion plants counting only the plants with over 1MWe capacity [9]. A separate source reports details on anaerobic digestion facilities including smaller plants, and as on the 31st March 2016 had records of 78MWe from 150 farm fed plants, and 141MWe from 104 waste fed plants [10]. For both of these groups, around 80% of the total generated biogas is used for CHP. This gives a total of 182MWe of CHP capacity, although only 69MWe of this capacity could be converted to flexible generation, and the remaining capacity has an operational requirement to process the incoming waste. However even in the cases where the feeding is not flexible, the running of the CHP units could still be changed to run on demand, and the available power could be increased by increasing the biogas storage capacity. These figures show that in the United Kingdom, there is a smaller amount of energy crop based anaerobic digestion systems, but still a significant number.

So whilst any optimisation techniques or new monitoring technology that are developed could be applied to both operating scenarios, it is more necessary for the agricultural biogas plants than the systems primarily interested in the handling of waste, as the waste handling installations are able to operate profitably in the absence of funding, whereas agricultural biogas plants will struggle financially and may be faced with closure.

#### 4. Inhibition Mechanisms

There are a range of mechanisms that can cause inhibition. One reason can be "wash out". The HRT (hydraulic retention time) of an AD plant is calculated by dividing the volume of the digester by the volume that is added each day. For example, a 1000m<sup>3</sup> digester with 50m<sup>3</sup> of liquid added per day would have a HRT of 20 days. If this HRT is less than the time that it takes for the bacteria to double, then washout occurs [11]. Under this condition, the bacteria growth rate is not sufficiently high enough to maintain a stable population, and so too much bacteria is washed away from the reactor. Washout primarily occurs when the level of volatile solids in the feedstock is too low, such as in slurries which contain large amounts of water. For feedstocks such as maize, the level of volatile solids can be in the range of 90-95% of the dry matter, and so a smaller amount can be fed when compared to slurry. This results in a longer HRT, giving the bacteria more time to reproduce before being carried out of the digester. By comparison, dairy waste contains approximately 10.5% volatile solids [12], requiring 9 to 10 times higher volumes to be fed in to the reactor in order to achieve the same organic loading rate. This higher loading rate leads to a higher probability of wash out.

A second cause of inhibition is organic overloading. When the volatile solids feeding level for a digester is too high, then the synergistic relationship between the microbes starts to break down. The first stages are able to cope better with the higher loading rate. The methanogenesis stage however at higher loading rates will not be able to convert enough of the volatile fatty acids to keep up with the rate at which they are produced. This results in the VFAs accumulating in the digester, which then results in the pH of the digester dropping causing a loss of alkalinity [13]. As the pH changes, the digester conditions are no longer optimal for the bacteria and their work rate drops. VFA accumulation can reduce the rate of hydrolysis and at very high levels can cause inhibition, even in cases where the process pH is optimal [14]. There are differing accounts of the effects of VFAs, with some publications showing that propionic acid can cause digester failure, and with others showing that propionic acid accumulates as a result of inhibition elsewhere, rather than causing it [15].

The drop in the work rate of the bacteria then results in a faster accumulation of VFAs, resulting in a further rate drop, and so this feedback can generate a quick process stop. This type of inhibition can occur at any stage, however if for example the hydrolysis stage is inhibited, then this will reduce the substrate consumption of the later phases, and the entire process will perform more slowly. However if the final stage (methanogenesis) is inhibited, then there are a build-up of intermediate products which is more difficult to recover from.

In addition to these inhibition mechanisms, there can be inhibition occurring separately as a result of the substrate composition, for example ammonia inhibition can occur when the feeding load contains high concentrations of ammonia such as poultry waste. Similarly, a high level of sulphur in the feedstock can lead to high H<sub>2</sub>S (Hydrogen Sulphide) concentrations which will also inhibit the microbes. Sulphide inhibition can occur when there are high levels of sulphates or other sulphur compounds in the feedstock fed to a digester.

This is more of a concern for anaerobic digestion containing waste streams of industrial process which tend to have higher levels of sulphides [16]. Similarly, the presence of heavy metals can also cause inhibition and process failure and are also more of a problem for specific industrial waste sources [16].

If the process is only slightly inhibited, then it is important to quickly correct the digester operating point to a stable state where all of the microbes at the different stages are able to function correctly. This change in operation can be achieved by reducing the OLR (Organic Loading Rate), or by changing the substrate composition. If the entire process has completely stopped then there is little chance of recovering the process, and instead the digester will be drained and refilled. Once refilled, it can take several months for the microorganisms to regrow and for biogas production rates to reach the same level that they were before the digester was drained. Clearly this has a high cost, and results in a reduced income for several months until the digester recovers to a similar performance level that it was previously operating at. This is the reason that feeding regimes tend to be conservative, in order to avoid the expensive problem of inhibition occurring.

Due to the anaerobic digestion process using synergistic relationships between microbial communities, the point at which inhibition begins is difficult to accurately predict. The communities are capable of adapting to new environmental conditions, and will adjust with time. As a result, any fixed values that are given, for example the feeding rate of volatile solids, or the target value for a specific process parameter, are not actually considering the characteristics of the microbes. The thresholds are typically chosen as reasonably safe thresholds that have experimentally been found to have a low failure rate. In order to optimise the process, thresholds are necessary for each individual digester with its associated microbial community.

As there are multiple stages in the process, it often occurs that inhibition of one stage can happen, but the later stages are still functioning. As a result, it may appear that the process is still functioning well until the inhibition finally propagates to the produced biogas, at which point it can be too late to recover [16].

## **5. Intermittent Production Data Analysis & Control**

By shifting the operation of a biogas plant from continuous to intermittent in order to provide power on demand, there is a potential financial benefit, and this can be achieved without significantly impacting the cumulative output of the digester [17]. Other research has shown that by using a continuously fed digester, and adjusting the feeding rate, it is possible for a digester operator to estimate the state of the digester and make decisions on the feeding levels based on the response to the changes in feeding rate [18]. The consequence is that when feeding a digester intermittently, there are large variations in the feeding rate, and by observing the change in gas production rate after changing the feeding rate, it is possible to make an estimate about the condition of the digester and whether the system is stable or approaching the maximum capacity. The measured change in the system

output following a feeding event will consider the entire process, and so the rate limiting step within the process will have an observable effect on the final output, which is the biogas production rate. By analysing the gas production rate, it is possible to estimate the digester condition and use this to control the feeding rate to reach a high feeding level whilst maintaining stable operation. Experimental results have shown that such analysis performs well when feeding materials that result in a fast response such as maize silage or milled grass silage, and by contrast with cattle slurry this was not observed due to washout [19]. This analysis was then able to control an ADM1 simulation [20] and converged on a stable level with daily feeding events.

## Conclusions

There is a change in the energy market which has been instigated by the reduction of costs for producing renewable energy sources such as wind and solar. These sources are weather dependant and as such are not a controllable energy source. Anaerobic Digestion has not experienced such a rapid reduction in cost, however is well suited to operate as an intermittent power source, which would enable generation at times when other renewable sources are not able to meet the demand. Such an operation will then provide further information about the anaerobic digestion process and can be used to control the feeding amounts to help maintain a stable operation. By using intermittent feeding, it may be possible to detect conditions leading to inhibition and reduce the feeding levels in advance, however it is not possible to detect other sources of inhibition such as washout by using such an analysis.

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